

**RESEARCH PROPOSAL**

FOR

**CONSTRUCTION VIBRATION ATTENUATION WITH DISTANCE AND ITS EFFECT  
ON THE QUALITY OF EARLY-AGE CONCRETE**

TO

**WISCONSIN HIGHWAY RESEARCH PROGRAM  
GEOTECHNICAL OVERSIGHT COMMITTEE**

DATED

**APRIL 1, 2005**

BY

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**Duration of Project: 3 years**

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## **CONSTRUCTION VIBRATION ATTENUATION WITH DISTANCE AND ITS EFFECT ON THE QUALITY OF EARLY-AGE CONCRETE**

### **PROBLEM STATEMENT**

On past WisDOT projects, engineers have been concerned about the potential damage to adjacent structures due to construction-induced vibrations from contractor operations such as pile driving and blasting. The Department of Commerce COMM 7 of Wisconsin Administrative Code regulates vibration requirements associated with blasting. The vibration levels noted in COMM 7 were established in order to place limits such that blasting does not cause injury or unreasonable annoyance to persons or damage to structures. COMM 7, however, does not address air and ground vibration resulting from pile driving or other related construction-induced vibrations.

Because of the limited research and regulation on this topic, the current WisDOT approach to determine the potential vibration-induced damage typically requires pre-construction surveys and/or inspections prior to construction-induced vibrations. Contractors must monitor construction operations with a seismograph. And, according to WisDOT Standard Specifications, contractors are limited on the timing and distance of concrete placement and distance of driving pile shells adjacent to concrete-filled piles. The Specifications only address pile driving vibrations with respect to the concrete placed within pile shells and not with respect to other recently placed concrete structures such as footings. The current approach is perceived as too restrictive in some cases and may contribute to longer construction periods and increased project costs. This proposed study has stemmed from the need to address potential damage to concrete-filled pipe piles and recently placed concrete structures that could be affected by pile driving vibrations. The study will focus on two research topics:

- The attenuation of potentially damaging pile driving vibrations with distance from the source.
- The effects of distance and curing time of concrete on the quality of recently-placed concrete exposed to pile driving vibrations.

### **RESEARCH OBJECTIVE**

The first objective of the research proposal is to investigate the two areas of interest of the proposal: (1) attenuation of potentially-damaging pile driving vibrations with distance and depth and (2) the effects of distance and age on the quality of concrete exposed to pile driving vibrations. An extensive technical literature review; evaluation of existing pile driving and vibration data from the contractor and from the Marquette Pile Load Test Program; field vibration monitoring; testing of field concrete samples subjected to pile-driving vibrations; testing of lab concrete samples subjected to vibration simulation; and finite element analysis modeling varying pile sizes, pile types, and hammers would be developed as supporting data to attain the second objective of the proposal.

The second objective is to use the supporting data to provide recommendations that would enable WisDOT to better define how pile-induced vibrations from different hammers affect the quality of concrete with distance and depth. These recommendations would include determining acceptable ground vibration levels and / or distances for recently-placed concrete based on curing time and / or compressive strength. The final report of the study can be used by WisDOT to develop economical, reasonable, and prudent project requirements with respect to pile driving vibrations and damage to adjacent concrete structures.

### **BACKGROUND AND SIGNIFICANCE OF WORK**

A preliminary review of literature related to construction-induced vibrations was conducted in response to the proposal. An abbreviated list of references is presented following the proposal. Previous research objectives have included determining threshold levels of human perception and annoyance from steady state and transient vibrations as well as preventing and assessing damage to structures and equipment.

Of the reviewed studies, the majority discussed attenuation of vibrations with distance and how vibrations related to the damage to *existing* structures from pile driving operations or blasting. The mechanics of

attenuation of vibrations from pile driving are fairly well understood. The Marquette Interchange project offers a good opportunity to compile a large amount of additional vibration data. The Marquette Interchange Project is the reconstruction of three major interstates I-43, I-94, and I-794 located in the heart of downtown Milwaukee. The area is surrounded by shallow-supported buildings, historical sites, and other facilities that could be damaged during construction activity. From 2003 through 2008, the Marquette Interchange Project involves construction of new structures such as bridges and retaining walls that require deep foundations. This project has been divided into 5 major contracts. Two contracts, Contracts C and S, will include more than 260 substructure units. The majority of substructure units will be supported by concrete-filled pipe piles that have an outside diameter of 14 inches and an allowable axial pile capacity of up to 200 tons. Dynamic testing is planned at each substructure unit on 10 percent of the piles or a minimum of 2 piles, whichever is greater. Contractors will also provide the WHRP research team with results from the construction vibration monitoring.

Of the additional studies reviewed, the effects of vibrations on curing concrete have only been addressed by a few. *To our knowledge, none have implemented in one study a field and lab program similar to the one described in this proposal.* Tawfig and Abichou (2003) indicated that only 9 of 26 state highway agencies surveyed in his study had Standard Specifications for controlling vibrations from pile driving operations. Tawfig and Abichou also synthesized that the specified vibration measurements varied from state to state and that vibration criteria for "green" concrete were not addressed by many state agencies.

Of those research studies that addressed the effects of vibrations on curing concrete, opinions and conclusions stated in the studies varied widely, as shown below:

- Committee of Deep Foundations concluded that "there are no detrimental effects due to vibration of concrete during its setting and curing period. There is evidence that beneficial effects may even be derived".
- Another ASCE publication, Design of Pile Foundations, recommends that pile driving should not be allowed within 100 feet of concrete which has not attained its design strength.
- Tawfig and Abichou observed within the first few hours after concrete placement, test results indicated that "green" concrete can withstand fairly high intensity vibrations. This same study concluded that compressive strengths of concrete samples subjected to vibrations until the end of the final setting time increased as the vibration amplitude increased up to a peak particle velocity (ppv) of 2 in/sec. The compressive strengths of samples subjected to greater vibrations were observed to slightly decrease. In their conclusion, however, Tawfig and Abichou recommended that construction vibrations around "green" concrete in drilled shafts be avoided to eliminate effects such as segregation, bleeding, and reduction in concrete stiffness and strength. They further state that a ppv of 2 in/sec was the most critical velocity for the concrete samples used in the investigation.
- NCHRP Synthesis 253 Report (Transportation Research Board) includes excerpts from a draft version of ACI 231-97, Chapter 5 under consideration, which states that a threshold of failure has not yet been reported in test programs cited, and that establishing ppv criteria in the 5 to 10 in/sec range for 2 to 7 day-old concrete should easily be demonstrable with limited compressive cylinder testing.
- Bastian describes three case histories in which compressive strength was found to be greater for concrete subjected to pile-driving vibrations compared to cylinders cured under normal conditions. One of the studies cited was from a 1929 Michigan Highway Department Report that is one of the first documented cases where tests were conducted specifically to determine the effect of pile driving vibrations on fresh concrete in nearby cast-in-place piles.
- Oriard provides guidelines for maximum allowable particle velocity for different curing ages of concrete. His guidelines indicate acceptable particle velocities in the range of 5 to 20 in/sec for curing concrete.

As stated by Wiss in his 1981 state-of-the-art report on construction vibrations, additional studies to evaluate the effects of vibration on "young" concrete are recommended. Literature dated after the 1981 Wiss recommendation, however, does not consistently address or conclude the effect of vibrations on curing concrete. Reddy in 2000 stated that although enough has been learned about concrete vibration during the past 50 years to insure that low slump concrete can be placed successfully, a better understanding of the interaction of vibration and fresh concrete is still desirable.

Due to the varying opinions and recommendations on this subject, it appears imperative that an additional research study be conducted to address the pile driving effects of vibrations on curing concrete. Little guidance and supporting data is available in current state design procedures to assist with determining safe distances between pile driving activities and curing concrete. This research study will combine ideas from previous research studies such as those discussed by Wiss, Bastian, Tawfig, and Hendriks. New techniques will also be adopted so that in a single study various parameters such as vibrations with distance and depth, and the relationship to the curing age and compressive strength are measured. *This research study will be unique in the way it incorporates various field and lab testing into one study.*

Preventing and evaluating the potential damage to adjacent structures from construction-induced vibrations is a critical part of planning for urban projects especially as city limits expand and the highway infrastructure boom from the 1960s exceed its service life in the upcoming decade. As the number of reconstruction projects increase, allocation of funds for transportation projects requires increasing attention. Providing more reasonable project requirements with respect to vibrations, concrete, and pile driving may be one way to reduce constructions costs, delays, and litigation.

## **BENEFITS**

Benefits of the study can be discussed in terms of the ability to make reasonable and economic decisions resulting in a better allocation of resources, and include the following:

- Estimating the potential for damage of recently placed concrete due to pile driving vibrations will result in improved design and construction recommendations. If this information is used in the design stage, construction documents can more adequately address what is necessary on individual projects. This could decrease construction and design costs of WisDOT projects as well as promote increased production rates during pile driving stages of construction. Currently, conservative designs and specifications have developed in some cases because the potential damage from vibrations cannot be reliably predicted and concerns cannot be adequately addressed. For instance, contractors are limited on when and at what distance they can place concrete from pile driving
- Evaluating the relationship of pile-driving vibrations with distance will provide a better understanding of damaging effects on nearby structures and may decrease liability exposure through improved design and construction practices.
- Recommendations resulting from this study will provide WisDOT guidance to modify current practices incorporated in the WisDOT Bridge Manual, WisDOT Facilities Development Manual, and Standard Specification for Highway and Structure Construction. Although beyond the scope of this research effort, our research team would be willing and available to assist with these future efforts if considered necessary.

## **IMPLEMENTATION**

A final report will be produced documenting our research approach, assumptions, findings, conclusions as well as the following tools:

- Step-by-step instructions of how to determine acceptable vibrations levels and/or distances based on the age and compressive strength of concrete through the use of graphs. These instructions are intended to be understandable and usable for the design engineers, contractors, and owners.
- Graphs illustrating peak particle velocity versus scaled distance as shown in Figure 1 will show how vibration levels decrease with distance. This information can be used to evaluate at what distance the vibration levels may have a minimal effect on concrete and existing structures.
- A series of graphs similar to Figure 2 that show how vibration levels from different hammer energies and distance affect the compressive strength of concrete with age. It is anticipated that as the distance away from the source increases, the impact or detrimental effect to the 28-day compressive strength of the concrete will lessen. This will enable the research team to determine a "safe" vibration level for a given mix of cured concrete in the plastic state (prior to initial set), after initial set, and during final-set stages at multiple distances from the source.

- A series of graphs illustrating the relationship between safe distances with the curing age of concrete as shown in Figure 3 will be developed by synthesizing the data collected from the previous 2 graphs. This information can be used to evaluate potential damage to curing concrete structures and to develop a relationship between permissible minimum pile driving distances as a function of concrete curing age.

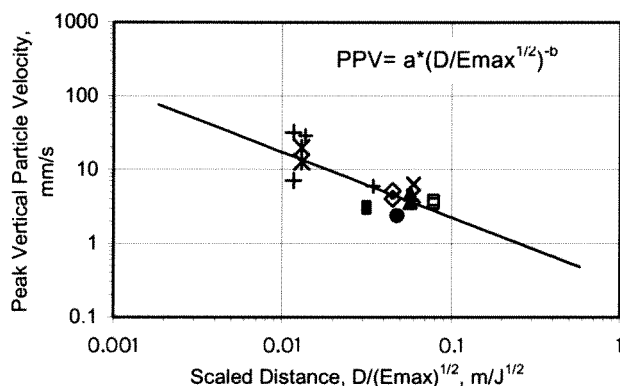


Figure 1

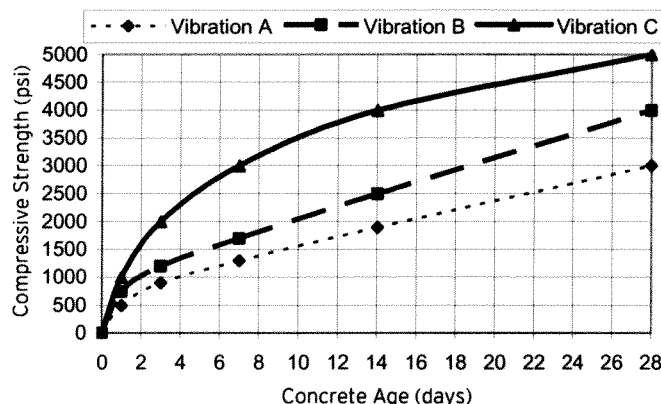


FIGURE 2

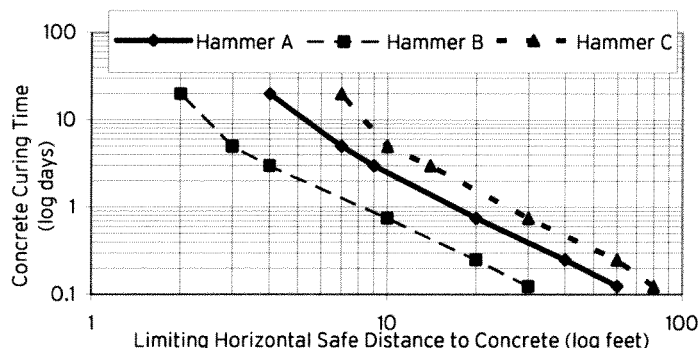


FIGURE 3

These step-by-step instructions and graphs can be used to improve design and construction recommendations in a manner that could substantially decrease construction costs and schedules. The information from the study could also be used to decrease liability exposure. For example, in some circumstances, it may be appropriate to use the information during litigation to refute unfounded damage claims. Liability exposure can be reduced through an improved design and construction practice. The ability to better predict attenuation of potential damage-causing vibrations and evaluate the potential for damage of nearby curing concrete reduces the likelihood of damage occurring.

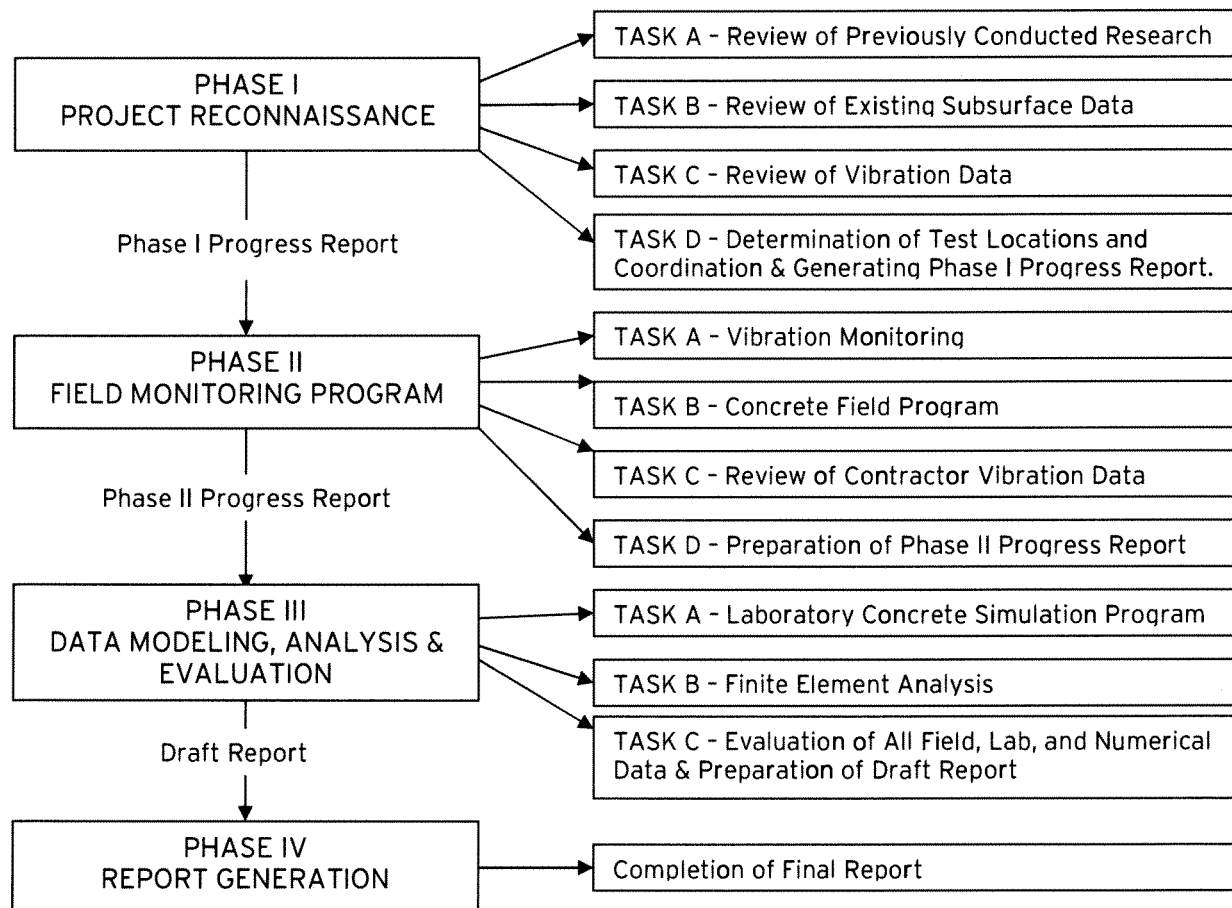
## DETAILED WORK PLAN

To meet the objectives of this study, four major phases will be completed. The Work Plan diagram on Figure 4 and bulleted list below summarize these phases:

- Phase I, Project Reconnaissance**, includes tasks that require review of existing conditions, vibration data, and literature in addition to determining field test locations.
- Phase II, Field Monitoring Program**, includes the tasks which require coordinating the program with the Contractor and Dynamic Testing Firm; installing the field instrumentation; and conducting the field monitoring program. The program will incorporate monitoring and evaluating attenuation of pile driving vibrations with distance and at depth at a large number of test sites. Full scale concrete samples of varying ages will be subjected to pile-driving vibrations at several distances. Emphasis will be placed on evaluating early-age concrete. These field samples will be compared with those tested in the laboratory in Phase III.
- Phase III, Data Modeling, Analysis and Evaluation**, includes synthesis of field data, an extensive laboratory testing program, and finite element analysis. The laboratory program will evaluate the influence of a wide range of peak particle velocities and frequencies of vibration and how that affects

the short-term and long-term compressive strength. Test results will be compared with control sets not subjected to vibrations. In addition, a finite element model will be developed to predict induced ground vibrations due to pile driving considering various pile driving equipment and excitation mechanisms and different pile types. The model will take into consideration the heterogeneity and anisotropy of the soil. After calibrating the numerical model to site-specific behavior, the model will be used to analyze various conditions of interest (different types of piles and hammers) that will complement the experimental results obtained from field vibration tests.

- **Phase IV, Report Generation**, is the final phase of the study which includes reporting the data and analysis generated from Phase I through III and generating the step-by-step instructions, tools or graphs relating safe distances with concrete age.



**FIGURE 4 – WORK PLAN DIAGRAM**

## PHASE I – PROJECT RECONNAISSANCE

**Phase I** will consist of four tasks: **Task A** includes an extensive literature search of previously conducted research; **Task B** consists of a review the subsurface data collected from the Marquette Interchange Project; **Task C** comprises of a review of the Pile Load Test Program results and vibration monitoring; and **Task D** includes determining field test locations based on Tasks A through C in addition to input and coordination with the Contractor and the Dynamic Testing firm.

A preliminary literature search was conducted in response to the proposal, and an abbreviated list of references is included following the proposal. As part of **Task A**, this search will be expanded as well as conducting interviews with key researchers and staff of departments of transportation on this subject. As Part of **Tasks B and C**, the review would include the subsurface, groundwater and previous vibration

monitoring information collected by Milwaukee Transportation Partners (joint venture between HNTB Corporation and CH2M Hill) for the Marquette Interchange. The Geotechnical Exploration Program included 118 borings within limits for Contracts S and C drilled in 2002 and 2003, 159 borings drilled in the 1960s, 15 monitoring wells, numerous lab testing on soil and rock samples, 24 pressuremeter test locations, 27 cone penetration tests, and 2 dilatometer tests.

As part of the Geotechnical Exploration Program, the area within Contract C and S was divided by MTP into four soil sectors (Sectors A through D) based on a general profile of soil and groundwater conditions encountered during subsurface exploration (MTP, 2003-2005). The majority of substructure units are located within Sectors A and B, and a minor percentage in Sector C. Sector A was defined as the region that did not contain organic soils, and generally was comprised of shallow-depth fill over alternating layers of silty clays and clayey silts embedded with layers of sands and silts. Sector B contained shallow depth fills over compressible organic silts and clays to significant depths underlain by lacustrine and glacial till deposits. Sector C, located near the Milwaukee River and I-794, is similar to Sector B; however, the organic materials are underlain by primarily alluvial deposits.

A pile load test program was also completed as part of the Geotechnical Exploration Program for the Marquette Interchange. The pile load test program comprised of driving 89 piles located at either 6 static load test sites (SLT-A to SLT-F) or 43 indicator pile sites (IPS-01 to IPS-43). Dynamic testing including Pile Driving Analyzer (PDA) as well as Case Pile Wave Analysis Program (CAP-WAP) was performed on each pile during driving and during subsequent re-strikes. During the load test program, vibration monitoring was conducted at various locations, which has been evaluated by HNTB Corporation in development of recommendations for the Marquette Interchange Project. The monitoring was performed to determine general vibration levels and if vibrations had the potential to cause damage to adjacent structures. Members of the research team were part of that effort.

**Task D** would include formulating all of the data in Tasks A through C and then determine the proposed locations for the Phase II field monitoring program. A Phase I Progress Report (electronic version) will be submitted to the Research Advisory Committee. The research team is suggesting that a Research Advisory Committee be established consisting of members of the Technical Oversight Committee. For Phase I, the committee would review and input into the proposed testing locations for the second phase of the study.

## **PHASE II - FIELD MONITORING PROGRAM**

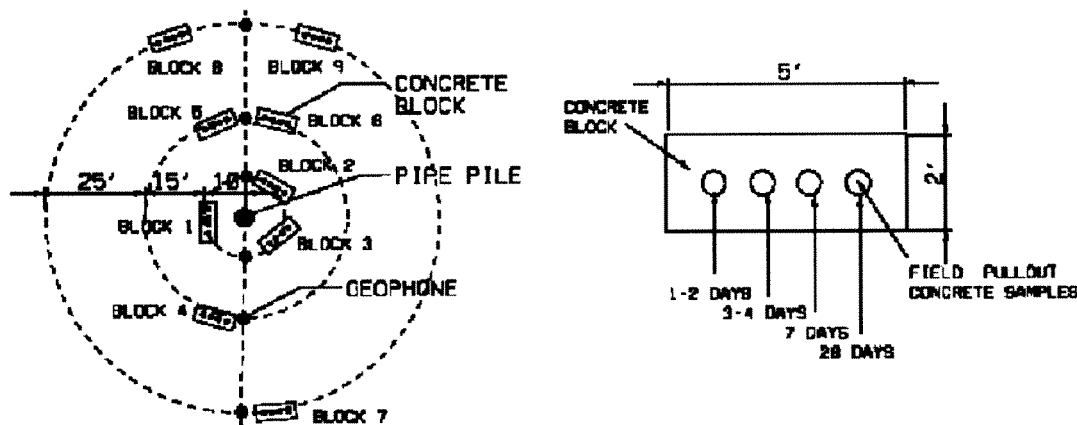
The field monitoring program will consist of four major tasks: **Task A** consists of collecting vibration data at the test pile locations; **Task B** comprises of installing and testing the full-scale field concrete samples; **Task C** consists of evaluating the contractor's vibration monitoring data; and **Task D** will be generation of the Phase II Progress Report.

Vibration and concrete data will be collected during construction on the Marquette Interchange. Because of safety concerns and the Owner Controlled Insurance Program (OCIP), the investigators and staff will be trained for site access prior to entering the site. The proposal assumes that field tasks will be coordinated with the respective contractors and dynamic testing firm to avoid contractor, research team, or project delays. The vibration data that was collected by MTP during the Pile Load Test Program determined that pile driving vibrations generally dissipated with distance according to a power equation dependent on hammer energy. Site-specific experience was one factor used to establish the field vibration monitoring program. Other factors, such as safety, the optimization of the quantity and quality of information that could be obtained from the study, and the coordination with the contractor, were also considered.

In order to determine vibration attenuation with distance, geophones are planned to be placed at given radial distances of 10, 25, and 50 feet along 2 radial axes extending away from the test piles that will be driven during the Dynamic Testing phase of the project (Figure 5). Test locations closer to the pile are more desirable but may not be practical from a safety standpoint and may interfere with contractor operations. Two axes of geophones were selected in order to generate enough data to evaluate

variability of readings at set distances and to provide a level of redundancy for this important phase of the study. A White Instruments Mini-Seis 1.0M, Vibra-Tech Everlert III, Everlert VE Seismograph, or equivalent with geophones will be used to measure vibrations. This equipment can record in both waveform and bargraph modes, but not simultaneously. The waveform mode does not monitor continuously and can record and store only about 20 events. Because pile driving vibrations are not expected to change rapidly, this mode is excellent for recording a large amount of information for an event. The bargraph mode also samples at a high rate but stores the peak level obtained over a programmed interval of time (say 10 second intervals), and can record all day. Our study will utilize both modes of data collection.

Geophones instead of accelerometers were selected as the majority of contractors and owners use this type of equipment for vibration monitoring. The geophones will be placed either on the ground surface or within 1 foot below the soil surface. Precise distance measurements will be made. It should be noted that the cost of the geophones, \$27,000, will be covered by cost sharing provided by UWM. The geophones will be synchronized in order determine relationships between distances and events. Vibration monitoring during Dynamic Testing allows the impact frequency and delivered hammer energy to be measured with Peak Particle Velocity, such that an attenuation equation will be generated in specific soil conditions. As a minimum, readings will be taken continuously for a certain time interval for every 5 feet of the test pile driven. Figure 5 presents a schematic of the one pile set-up.



**FIGURE 5 – SCHEMATIC OF TEST PILE LOCATION**

Vibration monitoring (**Task A**) will take place at 12 test pile locations. The locations will be divided proportionally in Soil Sectors A, B, and C to the number of piers and piles driven in each soil sector during construction. This results in 72 data collection points (12 test piles x 6 geophones) for every 5 feet of test pile driven. Recording in waveform mode, at least 120 measurements would be obtained for each test location and more than 1,440 sets of data could be collected for the field program.

During pile driving, three main wave types are generated: Rayleigh waves, shear waves and compression waves. Rayleigh waves are confined to a zone near the ground surface. Heckman, Richart, and others have stated that an estimated 67 percent of the total energy of elastic waves is in the form of Rayleigh waves. Rayleigh waves are more damaging in nature because they attenuate more slowly than the shear and compression waves. It is therefore the opinion of this research team that monitoring surface waves would be most beneficial. At one site, however, energy attenuation at depths will be measured. This site location will likely be in Sector A (stiff to very stiff silts and clays) where harder driving is anticipated in the upper 20 feet of the pile. A single geophone will be placed 10 feet below grade at 10, 25, and 50 feet from the test pile. A borehole will be drilled and held open by PVC pipe. The geophone will be placed at the bottom of the hole and synchronized in the same manner as the other 6 geophones. After completion of the test, the borehole will be abandoned according to DNR requirements. The depth of 10 feet below grade was selected because many structures such as pile caps, footings, and concrete pipe are located within 10 feet below grade and this effect is addressed to make our study as comprehensive as possible.

**Task B** will monitor pile-driving vibrations on recently placed concrete with variable cure times. The research of concrete will focus on the influence of vibrations on compressive strength as an indicator of concrete quality. Maturity meter monitoring will be considered as a means to evaluate the compressive strength of early-age concrete and for estimating concrete strength at various times. Consideration was also given to looking at items such as segregation, bleeding, microstructure, air void size and spacing, and other strength and durability characteristics and properties of concrete. The research team, however, will focus on the study of compressive strength with respect to curing time as this is widely used and recognized as a property of concrete quality. This approach would also be relatively easy for others to apply in future studies and adaptable to project design and construction applications.

During **Task B**, field-scale testing of concrete will be performed at three of the twelve **Task A** test locations. Prior to driving at each test pile, nine blocks of concrete (or three sets of three) will be placed to study the affect of vibrations on 3 cure times at 3 different distances. Each set will represent one batch or cure time of 4-8, 12-15, or 24-30 hours. The blocks in each set will be placed at the same distances of the geophones, 10, 25, and 50 feet from the pile. The blocks of concrete, approximately 2 feet wide by 5 feet long, will be earth-formed and constructed in the ground approximately 18 inches below grade. A schematic of the concrete block layout is shown in Figure 5. The concrete will be a standard WisDOT concrete design mix previously approved for use on the project. The mix design will be tested in the lab prior to the field monitoring program. A local ready-mix supplier will provide concrete for this phase of the study.

To determine how the long-term compressive strength of the concrete is affected, each block will have four cylinders (field samples) cast in a mold at the same time the blocks are placed. Cast-in-place, pull-out –cylinders (CIPPOCs) will be used for this stage of the project. CIPPOCs consist of double-sleeved cylinder molds for casting and removal of test cylinders to replicate curing conditions of mass concrete. The field samples (total of 36 cylinders = 4 cylinders x 9 blocks) will be removed the following day and transported to the UW-Milwaukee lab where the samples in each set will be broken at 1-2 days, 3-4 days, 7-8 days, and 28 days. An additional 12 concrete cylinders (4 per site) will also be made from the same batch of concrete as the blocks at a location away from construction vibration as a control set. Compressive strength tests will also be conducted on control samples to compare results, for a total of 120 concrete cylinders to be crushed during the field monitoring program (4 cylinders x 9 blocks x 3 sites + 12 control). A matrix showing the number of cylinders is below:

Block		1	2	3	4	5	6	7	8	9
Distance (feet from pile)		10	25	50	10	25	50	10	25	50
Break Time (days)	Cylinder	Batch A10	Batch A25	Batch A50	Batch B10	Batch B25	Batch B50	Batch C10	Batch C25	Batch C50
1-2	1	1A10	1A25	1A50	1B10	1B25	1B50	1C10	1C25	1C50
3-4	2	2A10	2A25	2A50	2B10	2B25	2B50	2C10	2C25	2C50
7-8	3	3A10	3A25	3A50	3B10	3B25	3B50	3C10	3C25	3C50
28	4	4A10	4A25	4A50	4B10	4B25	4B50	4C10	4C25	4C50

Batch A (cure time 4-8 hours prior to pile driving); Batch B (cure time 12-16 hours); (Batch C (cure time 24-30 hours)

**Task C** consists of comparing **Task B** vibration and concrete testing results with the construction vibration monitoring performed by the contractor. As **Task D**, a **Phase II Progress Report** will be drafted which summarizes the data collected and proposed the appropriate parameters to be used in the data analysis and evaluation phase. Parameters would include varying hammer energies, pile types, driven pile depths, peak particle velocities, distances and curing times to be simulated or modeled in **Phase III**. The **Phase II Progress Report** will be submitted electronically to the formulated Research Advisory Committee for review and input into the third phase of the study. The proposed parameters within the **Phase II** report would be based on data available near the midpoint of the study. Commencement of the third phase would need to occur by early 2007 in order for the project to be completed within the 3 years allocated in the RFP.

## PHASE III – DATA MODELING, ANALYSIS, AND EVALUATION

The Data Modeling, Analysis and Evaluation phase is comprised of three tasks: **Task A** consists of determining the quality of concrete strength of samples with variable cure times subjected to simulated vibrations from shake tables, **Task B** includes modeling vibration attenuation with distance and depth for variable subsurface conditions, pile types, and hammers, in a finite element analysis. **Task C** consists of evaluation and compilation of all data obtained in the study into a Draft Report.

In **Task A**, a laboratory testing program will be performed to determine the effect of pile driving induced vibrations on recently placed concrete. The effect will be evaluated by testing the concrete compressive strength and density of laboratory cast specimens. These procedures are described in ASTM C-39 and C-138. The lab program will consist of three sets of 30 cylinders each. Within each set, six batches consisting of five cylinders each will be made. Each batch will be subjected to vibration using a shake table readily available at UWM. The field vibration data collected in **Phase II** will be converted to equivalent sinusoidal signals with a specific frequency and varying peak particle velocities (example: ppv = 0.5–20 inch/sec). These signals will be used in subsequent shake table tests. As indicated in the Table below, batches A, B, C, D, E and F will be subjected to a constant vibration for 20 minutes using ppv's ranging from 0.5 inch/sec to 20 inch/sec. Four cure times prior to shaking will be used: 4-8, 12-15, 24-30, and 72 hours, as indicated in the same table. Once the cylinders are shaken, they will be tested to determine their compressive strength at 3, 7, and 28 days. Thus, the total number of cylinders needed for this task is 90 (5 cylinders x 6 batches x 3 sets). A matrix of a single set is shown below:

PPV (in/sec)*		0.5	2	5	10	15	20
Cure Time	Cylinder	Batch A	Batch B	Batch C	Batch D	Batch E	Batch F
4-8 hours	1	1A	1B	1C	1D	1E	1F
12-16 hours	2	2A	2B	2C	2D	2E	2F
24-30 hours	3	3A	3B	3C	3D	3E	3F
72-80 hours	4	4A	4B	4C	4D	4E	4F
No vibrations							
Control	5	5A	5B	5C	5D	5E	5F

\*PPV's will be at a given frequency and will be based on field test results from Phase II)

Special procedures or different testing times may be needed to evaluate the performance of early-age concrete. For example, maturity meter monitoring will be considered as a means to evaluate the compressive strength of early-age concrete and for estimating concrete strength at various times.

**Task B** in **Phase II** includes the development of a finite element model to predict induced ground vibrations due to pile driving considering three main aspects: (1) pile driving equipment or excitation mechanism (2) dynamic soil-pile interaction (3) surface and subsurface vibrations in the soil. First, driving equipments and accessories in both impact and vibratory driving techniques will be considered and the excitation mechanisms in both techniques will be modeled. The pile-soil interaction problem is investigated using a carefully-constructed numerical model that includes the pile and the stratified soil. The model can take into consideration the heterogeneity and anisotropy of the soil. Using the model, the field vibration due to impact and vibratory pile driving, will be studied in a layered media. The analysis of such complex systems can not be attained by closed-form analytical solutions, and that necessitates the use of numerical techniques such as the finite element method.

The finite element model will be calibrated using the results of the field tests conducted in Phase II. This is done by comparing the measured vibrations at different points with those calculated from the finite element model using the same value of excitation (energy and frequency) of the hammer(s) used in the field tests. The material properties of different soil layers will be obtained from available data including boring logs of the test site.

After calibrating the numerical model to site-specific behavior, the model will be used to analyze various conditions of interest that will complement the experimental results. This will include (1) the effects of different types of hammers, both impact and vibratory, with different energies and frequencies; (2) effects of pile type; (3) effect of depth; and (4) effects of soil stratification. The results of the finite element analysis will clarify the effects of the above factors on the propagation and attenuation of the stress waves caused by pile driving. The results will help establishing recommendations for acceptable ground vibration levels and distances for recently-placed concrete.

The last task in **Phase III** includes evaluation and compilation of the research data and generating a Draft Report. The Draft Report will be submitted to the Research Advisory Committee for review and comments prior to Phase IV completion.

## PHASE IV – REPORT GENERATION

**Phase IV** consists of finalizing the Draft Report for submittal.

## WORK TIME SCHEDULE

The estimated work time schedule is shown below:

Year	2005			2006				2007				2008			
Phase	Apr.	Jun.	Oct.	Jan.	Apr.	Jun.	Oct.	Jan.	Apr.	Jun.	Oct.	Jan.	Apr.	Jun.	Oct.
I															
II															
III															
IV															

## REPORTS

As discussed in the Workplan, four reports will be generated in addition to the quarterly reports. Quarterly reports and the three progress reports will be submitted electronically, and 85 hard copies of the final report are assumed. Phase I Progress Report will be submitted in December 2005. It will summarize the data collected in Phase I and provide recommendations for field testing locations. Phase II Progress Report will summarize the available field monitoring program data and propose variable parameters to be used in Phase III lab simulation and finite element modeling. Phase II Progress Report is anticipated to be submitted in Winter 2006. The Draft Report is intended to be submitted in January 2008 for review prior to completion of the Final Research Study Report. The Final Report will incorporate comments received from the research team as well as WHRP. It is assumed that WHRP will have a 1 month review time and then the Final Report can be submitted in August 2008. In summary, our Final Research Report would include but not be limited to:

- Review of existing conditions, vibration data, and previous research
- Compilation of ground motion data obtained from the field program, including distance-attenuation graphs.
- Results of field and laboratory tests of curing concrete subject to vibrations.
- Evaluation of effects of pile driving vibrations on curing concrete, including discussion of the laboratory simulation and finite element modeling of behavior of vibration data with distance, depth, and variable hammer energies.
- Step-by-step instructions and graphs used to determine the safe distance of pile driving to curing concrete.